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Groundwater impact of open cut coal mine and an assessment methodology: A case study in NSW

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Abstract

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Groundwater impact of open cut coal mine and an assessment methodology: A case study in NSW

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ABSTRACT

Large scale open cut coal mining operations have significant impacts to groundwater in surrounding areas in both active and post-mining phases. The prediction of water inflows into a surface mine excavation is one of the many components involved in mine design phase. Groundwater performance also reacts to mining activities from the operational, economic and safety implications perspective. Under NSW planning legislation, as part of the comprehensive risk assessment, a groundwater impact assessment has to be conducted for a coal project to predict and mitigate the impacts in consideration of the government requirements. In this paper, the groundwater assessment modelling of mine pits was discussed in predicting of groundwater inflows and reviewing analytical and numerical approaches. A methodology of groundwater impact assessment for an open cut mine in NSW with a three-dimensional groundwater flow model Modflow Surfact demonstrated its functions in simulating the project's impacts on the groundwater regime. The key findings with mitigations are discussed and recommended in the paper to reduce impacts on groundwater and fulfil regulation requirements in NSW.

1. Introduction

Open cut coal mining is practiced in many parts of the world including Europe, South Africa, China, USA and Australia. Operations are commonly on a massive scale with individual mine pits sometimes exceeding 10 km^2 and 200 m depth. The very significant changes to the landscape and the disturbance of subsurface conditions are not without impacts to the environment. Most open cut operations intersect the natural water table, and all will create substantial catchments for rainfall and runoff. Noise and dust issues are caused by the mining activities and exposure of the open cut pits.

Open cut coal mining in New South Wales has resulted in mine pit depths of 150 m or more below the natural water table, and the backfilling and reshaping of more than 10 billion cubic meters of spoils waste rock. Groundwater can represent a problem during surface mining and its removal can prove costly. Not only does groundwater make working conditions more difficult, but piping, uplift pressures and flow of water into the pit can lead to erosion and failure of the sides. Under high pressure of sub-surface water gradients soils and weakly cemented rock can disintegrate. Excessive flow of groundwater can lead to pits flooding.

Estimation of water inflow to a surface mining operation is a necessary requirement for mine drainage design. The paper briefly describes the impacts on groundwater by mining advancing activities and provides an introduction to a methodology of groundwater impact assessment by a case study in Gunnedah Basin NSW. A groundwater assessment was conducted following by a mine optimization to mitigate impacts to adjacent agriculture lands and fulfil regulation requirements.

1.1. Relevant water legislation in NSW

The *Water Act* 1912 regulated activities which relate to or impact upon water sources in NSW including provisions for the licensing of taking of water from water sources. In general terms, the proponent will need to hold *Water Access Licences* to take water if, as a result of or in connection with, the mining activity carried out by the proponent, water is removed or diverted from a water source or water is relocated from one part of an aquifer to another part of an aquifer, subject to a *Water Sharing Plan*.

From a planning perspective, the Director-General's Environmental Assessment Requirements for the water assessments for

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the Project provided by NSW Department of Planning and Environment are under Section 78A(8A) of the Environmental Planning and Assessment Act 1979. The NSW Office of Water requires the EIS demonstrate the impacts on groundwater. The Federal Department of Environment also requires water study under EPBC Act in recent years.

2. Open cut coal mining and its impacts on groundwater

2.1. Open cut coal mining methodologies

The open cut mining method requires the efficient removal of overburden and interburden strata in order to access coal seams. An open cut pit is normally commenced through excavation of a box cut or initial slot into an area where the pit basal seam subcrops and the stripping ratio is low. The pit is then progressively developed along strike and down dip for distances of many kilometers. Waste rock known as spoil material is initially dumped 'out of pit' until a sufficient pit area has been excavated to enable in pit dumping. The stripping and removal of overburden to access many seams, is a continuous process. Overburden is displaced by blasting and the resultant muck pile is loaded and transported to the spoils dump area. Following overburden stripping, coal seams are removed using either ripping and loading, or blasting and loading. The coal is then transported to a preparation plant for primary crushing and washing if required [1].

A typical open cut pit section usually develops a number of benches. Dragline or truck and shovel loading operations are common while some operations utilize both at that same mine. The thickness of the overburden to be removed normally dictates the configuration of blast holes and the type and size of loading equipment. Overburden in thin and mediate thickness is normally blast fragmented to a muck pile size distribution that is amenable for front end loaders, hydraulic shovels while greater thicknesses are fragmented for electric shovel or dragline [1]. Haul trucks ranging from 150 to 300 tonnes capacity then transport and dump the waste rock. Dozer push and frond-end loaders are also used to mining multiple thin coal seams in NSW.

2.2. Groundwater impacts

The groundwater inflow to a mining excavation is mainly a consequence of the interaction of groundwater system, hydro geological characteristics of the rock mass and the mining geometry. The water inflow regime is determined by the incision of one or more aquifers by the mining excavation and the relative hydrogeological characteristics of the various aquifers. Inflow of surface water to a mining excavation can be predicted by hydrological balance investigations of a mining catchment [2]. The water in a shallow surface mine may originate solely from a surface source and from the atmosphere in the form of precipitation.

Operations below the water table can cause several operational, economic and safety implications. The active mining phase for an open cut pit can span periods of 20 years to more than 50 years before closure. During the active period there are significant impacts on the groundwater systems contained within the coal measures and the potential for impacts on shallow alluvial aquifer systems and groundwater dependent ecosystems. These impacts can be considered as either hydrophysical loss of aquifer pressures and consequential leakage from remote aquifers or hydrochemical mixing of ground waters, salinity from waste rock spoils [3].

The prediction of water inflows into a surface mine excavation is one of the many components involved in mine design phase. The open cut mining footprint, mining sequence, pit depth, and the physical measurements of the cuts involved in the digging cycle have temperate impact on the groundwater [4]. The mining exposure area of the active mining should be designed and optimized during mine planning phase to mitigate unnecessary environmental impacts.

3. Groundwater assessment modelling of mine pits

3.1. Prediction of groundwater inflows into surface excavations

The complexity of the relationship between aquifer type, aquifer characteristics, flow regime and mining excavation often complicates mine water inflow prediction. The flow regime depends on the type of conducting medium. In an unconsolidated sedimentary sequence where groundwater movement is through inter-granular pore-spaces, flow is essentially linear. On the other hand, in a rock sequence in which it is the secondary processes like fracturing and faulting that provide the conducting medium, flow is predominantly non-linear. Surface mining excavation serves as a natural groundwater discharge point. Near the excavation, there is invariably, a vertical component of flow and high hydraulic gradient which often leads to turbulent flow and negates analysis by Darcy's Law [2]. Non-linear flow equations are therefore valid. The rate of inflow is generally computed from equations which relate the hydraulic head loss in and flow of groundwater through the porous geological strata. Prior knowledge of aquifer hydraulic characteristics and pit geometry is necessary. The aquifer parameters are obtained from detailed hydrogeological investigation of the mine site and pit geometry from the mine plan.

3.2. Analytical approaches for surface mine water inflow prediction

The analytical approaches for estimating groundwater inflow to surface mining excavations are based on drawdown theory and can be broadly grouped into two as follows:

(1) Equivalent well approach

This approach assumes that dewatering of the surface mine is carried out by use of an imaginary pumping-out borehole (fully penetrating the entire saturated thickness of the aquifer) from which water is pumped out at a uniform discharge rate in order to lower the piezometric level of the aquifer to below the mining horizon at the mine boundary [2].

Various methods of approximating a mine model to an equivalent cylindrical well and estimating input parameters for the equivalent well model were researched by previous study. Normally the mine excavation is envisaged as a large diameter well. Where the mine has the shape of a square or rectangle, as is the case in most strip mines, then, an equivalent radius for the well is calculated using the equation given by Mansur and Kaufman [5].

$$r = \left[\frac{2}{\pi}\right]\sqrt{(Y.W)}$$

where Y is the length of the mine, m; W the width of the mine, m; and R the equivalent radius, m.

(2) Two-dimensional ground water inflows

Recent research has witnessed major developments in the application of two-dimensional flow equations to the determination of steady state and transient drawdown in large earth excavations.

When a surface mine works below the water table, groundwater flows from the incised aquifer into the excavation. Flow regime is essentially two-dimensional. Remote from the excavation, flow is linear but near the excavation there is vertical component of flow and the flow is non-linear. The approach is advantageous in that it is often compatible with the quantity and quality of hydrogeological data available. However, the simplified flow assumptions become invalid under certain conditions which include the near the seepage plane, in the region of vertical impervious boundary, etc. [2].

(3) Comparison of equivalent well and two-dimensional approaches

The simplest comparison between the two approaches can be made using equations for linear, steady state flow in a leaky aquifer. The relevant equations using standard notion are as follows:

Equivalent well approach, $Q = \dfrac{4\pi TDw}{W(u, r/B)}$

Two-dimensional approach, $Q = 2\dfrac{T}{B}DwY\ B = \sqrt{\dfrac{LL'K}{K'}}$

where B is the leakage factor, m; Q the total flow rate from both excavation faces, m^3/d; Y the length of the cut or high wall, m; T the transmissivity of aquifer, m^2/d; Dw the drawdown at excavation face, m; L the thickness of aquifer being dewatered; and K the hydraulic conductivity of the geologic formation, m/d [2].

3.3. Numerical methods

The application of finite difference, finite element and boundary element techniques predicts the likely quantities of inflow, elucidates the pattern of water movement and identifies regions where flow relates are particularly large. Flow calculations using mainframe computer packages are quick and cheap to perform, making it possible to analyse water problems associated with several scenarios.

Coupling surface and subsurface flow processes is a difficult mathematical task. Operations managers responsible for mining, water resources, and environmental remediation projects are looking for tools that will help them find solutions to complex planning challenges. The attempt is to decouple the two processes, focus on one of the two, and simplify the other process to a set of empirical parameters and functions. There are lots of computational tools and applications available in the market with Modflow and HEC-RAS as the most widely used codes [6].

4. An assessment methodology and modelling – A case study in NSW

A groundwater impact assessment was undertaken by Watermark Coal Project which is located in NSW Gunnedah Basin, to characterize the existing groundwater system, predict inflows into the mining areas throughout the life of the project, predict groundwater recovery levels and conditions post-mining, assess the impacts of the project on groundwater sources, and recommend measures to mitigate and manage impacts.

Modflow-Surfact was used to simulate the project's impacts on the groundwater regime which is the most widely used code for groundwater modelling and is presently considered an industry standard. Modflow-Surfact Flow groundwater simulation software features many robust methods and enhanced simulation capabilities for handling complex saturated/unsaturated subsurface flow and transport processes. The model includes the current understanding of the interactions between the aquifers within the project boundary and the regional groundwater system [7].

4.1. Data review

A desktop assessment was undertaken to review data collected as part of the field investigation program and previous hydrogeological investigations, including laboratory core testing, radiocarbon and tritium dating, definition of the edge of the alluvium and buffer zone properties. The information acquired from the desktop assessment was considered as inputs in the development of the groundwater model.

4.2. Modelling objectives

The objective of the groundwater modelling is to produce an output that represents the current understanding of the interactions between the aquifers at the project boundary and the regional groundwater system. The design, construction and calibration of the model were all tailored to meet these objectives as well as providing a framework for future iterations of the model following the addition of new data. The objectives of the modelling were to estimate groundwater seepages to the open cut Mining Areas over the 30-year project life, to predict the changes in groundwater drawdown to surface flows and other groundwater users due to project operations; and to identify areas of potential risk where groundwater impact mitigation/control measures may be necessary.

4.3. Model design

Two separate models were constructed for the project, a calibration model and a predictive model. The groundwater model was calibrated via two processes; a steady state calibration and a transient calibration. The aim of the calibration process was to adjust aquifer parameters and stresses to produce the best match between the observed and simulated water levels and fluxes.

Model extent and boundary conditions: the model grid is about 75 km wide (E-W) and 91 km long (N-S). This domain was developed to minimise any modelling boundary effects within the area of interest of the immediate surrounds of the project [8].

Model layers: seven key hydro stratigraphic units were identified that control groundwater flow in the project boundary and on a regional scale.

Grid and cell size: two separate models were constructed for the project. The calibration model had a larger cell size, which reduces the total number of cells and therefore the time required to run the model. Once a satisfactory calibration was achieved, the grid size in the model was refined around the project boundary to allow a more detail in the geology and mining to be simulated, referred to as the predictive model.

Fig. 1 presents cross-sections through the model grid in relation to the geological layers and the grid refinement for the predictive refined model.

Aquifer properties: starting hydraulic parameters were determined from extensive hydraulic testing at the project boundary, in combination with calibrated parameters from previous modelling in the same catchment. Where data was unavailable, textbook and extra-regional data were incorporated into the model.

Recharge: average annual rainfall recorded in local stations across the catchment was interpolated to create a rainfall distribution map.

Faults: there are a number of identified fault structures which compartmentalise groundwater flow across the boundary and are simulated in the model.

4.4. Predictive groundwater model

The model grid is approximately 75 km in width (east to west) and 91 km in length (north to south). This domain was developed

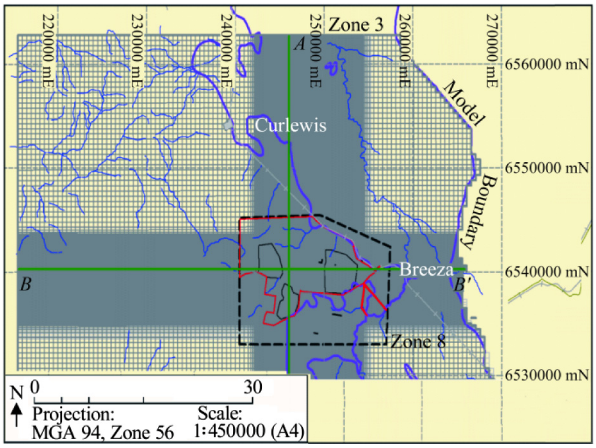

Fig. 1. Cross-sections through the model grid in relation to the geological layers.

to minimise any modelling boundary effects within the immediate surrounds of the project. The calibration model domain was constructed using cell sizes of 500 m × 500 m, which further refined to 250 m × 250 m cells within the project boundary. The calibration model included a total of 305,921 cells, comprising 27,811 cells per layer (11 layers).

The groundwater model was calibrated via two processes; a steady state calibration and a transient calibration. The aim of the calibration process was to adjust aquifer parameters and stresses to produce the best match between the observed and simulated water levels and fluxes. The calibration of the model followed the objectives set out in the Australian Groundwater Modelling Guidelines by Barnett et al. [9].

4.5. Calibration

The groundwater model was calibrated by adjusting aquifer parameters and stresses to produce the best match between the observed and simulated water levels and fluxes. A well-calibrated regional model indicates that the model closely replicates real world hydrogeological conditions, the first modelling objective, and therefore provides confidence in the predicted changes to the groundwater regime due to mining.

4.6. Verification

In order to verify the performance of the regional groundwater model, the transient ground water model was extended by three quarters to replicate groundwater levels from mid-2011 to March 2012. Several readings from the project database were assessed against the simulated levels.

5. Impact assessment findings

The groundwater model simulated the existing groundwater conditions and provided predictions of the potential changes in the local and regional groundwater regimes as a result of future mining activities including Eastern, Southern, and Western pits.

5.1. Mining area seepage

It is predicted that seepage will vary throughout the mine life, which is due to the mine depth, strata being mined and hydraulic gradients induced by the depressurisation. Groundwater seepage into the mining areas is estimated at approximately:

(1) Less than 500 m^3/day in the Eastern mining area until Year 17 (derived mainly from weathered interburden layers);
(2) 2200 m^3/day in the Southern Mining Area and 1250 m^3/day in the Western Mining Area from Year 17 to Year 24 until closure (derived mainly from saturated weathered to fresh clare sandstone) [8].

The contribution of seepage from the coal seams is relatively low. This is due to the low hydraulic conductivity determined from the field investigation program and adopted in the model. The groundwater seepage into the mining areas averages 500 m^3/day over the life of the project. The peak annual average seepage into the mining areas is estimated at 2200 m^3/day in Year 23 as mining advances through higher permeability material such as the clare sandstone unit. Groundwater seepage reduces as the mining area is backfilled following mining [8].

5.2. Changes in potentiometric surface/water table levels Permian Formations drawdown

Fig. 2 presents the predicted zone of depressurisation for the Melvilles seam for years 12.5, 21, 25.5 and 30. The movement of the mining areas gradually changes the extent zone of depressurisation over the 30 year project life.

The depressurisation induced by operations in the eastern mining area extends to a maximum of 1.8 km in Year 21. Groundwater levels are predicted to reduce to 3 m or less in the Permian Formations underlying the Narrabri Formation, laterally extending up to 0.7 km, and 1 m or less in the Permian underlying the Gunnedah Formation [8].

The model indicates groundwater levels begin to recover after the backfilling of the eastern mining area and southern mining area. This is due to seepage into the OEA from the mining area walls and from rainfall recharge. In the southern and eastern mining area, this results in groundwater levels recovering to higher than pre-mining levels.

5.3. Changes to surface water flow

Once mining commences, the Permian becomes depressurised, and within the zone of influence, upward flow from the Permian to the alluvium is predicted to reduce. The total additional flow from the Mooki River to the underlying aquifer totals 0.32 million m^3 at the end of the project life.

When the post-mining loss is considered the total additional flow through the Mooki River to the underlying aquifer due to the project is 0.49 million m^3. This is equivalent to an average of 0.016 million m^3/year over the project life or less than 0.02% of the mean flow along the river at Breeza.

5.4. Changes to water quality

The seepage water quality impact assessment confirmed that existing groundwater aquifers within and adjacent to the project boundary have salinity concentrations equal to or significantly greater (up to 10 times greater) than the seepage predicted to be produced from overburden and interburden. The average salt load for each mining area ranges between less than 0.1–0.34 g/of seepage zone per day.

5.5. Post-mining recovery of groundwater levels

The model indicates groundwater levels begin to recover after the backfilling of the eastern mining area and southern mining area eventually exceeding pre-mining levels. This is due to a higher recharge rate on the overburden material than the pre-mining con-

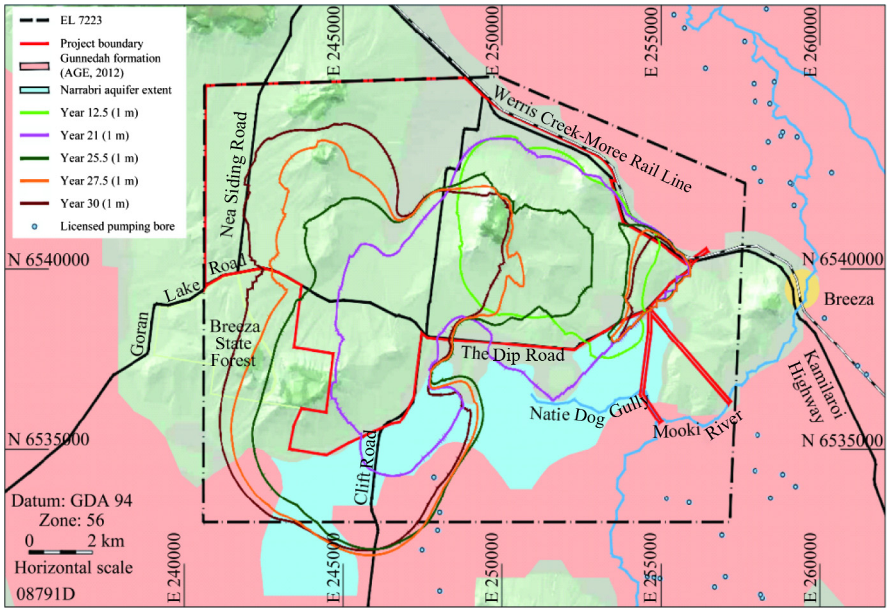

Fig. 2. Groundwater depressurisation zone–Melvilles coal seam.

dition. The higher recharge rate and rehabilitated landform mean that a zone of seepage occurs at spill points, which are topographic low points at the base of OEAs.

6. Mitigation and management

During the groundwater assessment process, the mine planning of the project also was optimized in pit sequencing and backfilling and final void location. As part of the *Environmental Management System* for the project, a *Water Management Plan* will be prepared to include the mitigation and management measures outlined below.

6.1. Monitoring network and monitoring groundwater levels

The existing groundwater monitoring network for the project is deemed adequate and will continue to be utilised. However, additional monitoring bores will be installed within the predicted zone of depressurisation to assess the extent and rate of depressurisation against model predictions.

The project manually monitors groundwater levels on a monthly basis through the current ground water monitoring network. Yearly audits of the performance of the monitoring network will be included as part of the annual review and optimization of the monitoring sites and frequency will be undertaken, where required.

6.2. Groundwater quality

The project currently collects groundwater samples from the groundwater monitoring network on a quarterly basis for laboratory analysis of pH, EC, TDS, major and minor ions and trace elements. This monitoring regime will continue for the life of the project.

6.3. Groundwater seepage

Samples of pumped groundwater seepage into the mining areas will be collected as part of the seepage monitoring program for the project with the objective of providing an early indication of any mixing of shallow alluvial groundwater with the Permian Formations. The seepage monitoring program will include recording of the time, location and volume of any unexpected increased groundwater outflow from the high wall and end wall; and monitoring of water pumped from the mining areas for the same analytical suite outlined in the groundwater quality monitoring program, etc. [8].

6.4. Management of existing groundwater users

If requested by the landowner, all private bores within the zone of depressurisation with a predicted drawdown of greater than 0.25 m as a consequence of the project will be monitored, for flow, water level and quality to validate model predictions and/or provide early warning of anomalous results.

6.5. Water licensing

The relevant water licences will be required to account for water taken as a result of the project.

7. Conclusions

Large scale open cut coal mining operations with significant changes to the landscape are not without impacts to ground water in surrounding areas in both active and post-mining phases due to its footprint, pit depth, mining sequence and dumping strategy. Groundwater performance also reacts to mining activities from the operational, economic and safety implications perspective. A dynamic optimization and monitoring program is recommended to be in place.

Groundwater model needs to be developed competently and fit for purpose for addressing the potential environmental impacts from open cut mining areas and for estimating indicative dewatering rates. A methodology of groundwater assessment and modelling with Modflow Surfact was introduced and case-studied in this paper. Mitigation solutions were also recommended in the paper to reduce impacts on groundwater and fulfil regulation requirements in NSW.

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